

LETTER TO THE EDITOR

Interior matter estimates of the X-ray pulsar in SAX J1808.4-3658 from mass-radius and rotation measurements

Nana Pan¹, Li Zhang¹, Xiaoping Zheng¹,

The Institute of Astrophysics, Huazhong Normal University, Wuhan 430079, Hubei, China
e-mail: Pannana@phy.ccnu.edu.cn
e-mail: zhxp@phy.ccnu.edu.cn

Received.....; accepted.....

ABSTRACT

Aims. To constrain the equation of state of super-nuclear density matter and probe the interior composition of the X-ray pulsar in SAX J1808.4-3658. In our estimation, we consider both its persistent 2.49 ms X-ray pulsations discovered by Wijnands and van der Klis from using the Rossi X-ray Timing Explorer, which is interpreted to come from an accreting-powered millisecond X-ray pulsar in the low mass X-ray binaries, and the corresponding mass-radius data analyzed of the light curves of SAX J1808.4-3658 during its 1998 and 2005 outbursts by Leahy et al. from assuming a hot spot model where the X-rays are originated from the surface of the neutron star.

Methods. The interior composition of the X-ray pulsar in SAX J1808.4-3658 is obtained from comparing the mass-radius relations, Keplerian motions and gravitational wave radiation instabilities of the predictions under different theoretical models with the analytically mass-radius district and rotation frequency of observational data.

Results. We show that SAX J1808.4-3658 may include the exotic matter such as hyperon or quark matter, but we can't distinguish the star with hyperon matter from quark matter.

Key words. dense matter — gravitation — stars: neutron — stars:rotation — stars:oscillations

1. Introduction

The properties of nuclear matter under extreme conditions are correlative to the in-depth experiment and theoretical research of the heavy nuclear physics and nuclear astrophysics intimately. Neutron stars provide us a unique spherical environment to study the properties of matter with low temperature and high density. Since the discovery of the first pulsar by Hewish et al. (1968) and then the confirmation of it to be a fast rotational neutron star by Gold and Pacini (1968), the compositions and properties of the interiors of neutron stars have attracted much attention (Pandharipande 1971, Glendenning 1985, Glendenning et al. 1992, Sahu et al. 1993, Thorsson et al. 1994, Alford & Reddy 2003). If we have made this significant problem clear, it would modify our understanding on the structure of the matter, strengthen the cognition about the formation of the universe and in all contribute most to the research of astrophysical physics, nuclear physics and particle physics.

However, in fact due to the uncertain nuclear physics, the equation of state for neutron star at super-nuclear density is still an indeterminacy, on which the maximum mass, radius and rotation frequency depend strongly. Many investigators spontaneously expect to probe the matter under these conditions and constrain or rule out some equations of state through astrophysical observations (Glendenning & Moszkowski 1991, Lattimer & Prakash 2004, Lackey et al. 2006, Lavagetto et al. 2006, Klähn et al. 2006, Lattimer & Prakash 2007, Pan & Zheng 2007). Although researchers universally impose the inferred masses and radii or rotation frequencies for pulsars on the equations of state, their

common treatments cannot uniquely examine and distinguish all the classes of compositions inside neutron stars, i.e. it could rule out neither traditional neutron stars nor hyperon stars or quark stars determinately. This problem should be carefully considered in other effective ways for the further estimation.

2. The X-ray pulsar in SAX J1808.4-3658

In this letter, we mainly estimate the X-ray pulsar in the transient X-ray burster SAX J1808.4-3658. Wijnands and van der Klis discovered its persistent 2.49 ms X-ray pulsations from using the Rossi X-ray Timing Explorer, and interpreted them to come from an accreting-powered millisecond X-ray pulsar in the low mass X-ray binaries (Wijnands & van der Klis 1998). Recently, Leahy et al. have analyzed its light curves during 1998 and 2005 outbursts to get the corresponding mass-radius data from assuming a hot spot model where the X-rays are originated from the surface of the neutron star (Leahy et al. 2008).

3. Probing stellar matter

In what follows, we present our approach to probe the matter composition of the X-ray pulsar in SAX J1808.4-3658 using the two observational characteristics mentioned above.

3.1. Mass-Radius estimates

The structure of a neutron star is determined by the local balance between the attractive gravitational force and the pressure force of the neutron star matter. The X-ray pulsar in

Table 1. Summary of equations of state A1-D1 introduced in the text, here compositions refers to the interacting components, n - neutrons, p - protons, e - electrons, H - hyperons and Q - quarks. GC and MC represent the deconfinement phase transition under Gibbs and Maxwell constructions respectively. RMF is the abbreviation for relativistic field theoretical approach in the mean field approximation, MIT the simple MIT bag model, eMIT the effective mass MIT bag model, APR the equation of state of Akmal, Pandharipande and Ravenhall using the variational chain summation, pQCD perturbative QCD corrections, and BBG the Brueckner-Bethe-Goldstone many-body approach.

| Symbols | Approaches | References | Compositions |
|---------|------------|-------------------------|--------------|
| A1 | RMF | Glendenning (1997) | npe |
| A2 | RMF | Lackey et al. (2006) | npeH |
| A3 | RMF+MIT | Pan & Zheng (2007) | npeQ (GC) |
| A4 | RMF+eMIT | Zheng et al. (2007) | npeQ (MC) |
| B1 | APR | Akmal et al. (1998) | npe |
| B(2-3) | APR+pQCD | Alford et al. (2005) | npeQ (GC/MC) |
| C1 | BBG | Nicotra et al. (2006) | npe |
| C(2-3) | BBG+MIT | Nicotra et al. (2006) | npeQ (GC/MC) |
| | | Fahri & Jaffe (1984) | |
| C4 | BBG | Baldo et al. (2000) | npeH |
| D1 | eMIT | Schertler et al. (1997) | Q(u,d,s) |

SAX J1808.4-3658 rotates at 2.49 ms, which in fact should be solved through the perturbative approach of the non-rotating equilibrium configuration in the framework of general relativity (Hartle 1967, Hartle & Thorne 1968). But the rotation corrections of the radii and masses are about 10% and 2-3%, which couldn't affect our results significantly here, the non-rotating approximation suffices.

According to the Tolman-Oppenheimer-Volkoff theory (TOV) under the consideration of the effect of general relativity, the structures of spherically symmetric static neutron stars could be determined by a set of equations (Tolman 1939, Oppenheimer & Volkoff 1939):

$$\frac{dp(r)}{dr} = -\frac{[\epsilon(r) + p(r)][m(r) + 4\pi r^3 p(r)]}{r[r - 2m(r)]}, \quad (1)$$

$$\frac{dm(r)}{dr} = 4\pi r^2 \epsilon(r). \quad (2)$$

($G = c = 1$) where $p(r)$ and $\epsilon(r)$ are the pressure and energy density of the matter at the radius r , and $m(r)$ is the total mass inside the star within a sphere of given radius r :

$$m(r) = 4\pi \int_0^r \epsilon(r') r'^2 dr'. \quad (3)$$

After the equation of state of the star $\epsilon(r) = \epsilon(p(r))$ is given, the TOV equations could be solved as an initial value problem. For a given equation of state, there exists a unique relationship between the stellar mass and radius. Thus different mass-radius relations obtained by considering various equations of state could be used to distinguish one from another.

As we have mentioned before, the neutron stars actually could have many classes. Besides traditional neutron star (A1, B1, C1) that mainly consists of neutrons (Glendenning 1997, Akmal et al. 1998, Nicotra et al. 2006), when hyperons become populated in addition to the nucleons, it corresponds to the hyperon star (A2, C4) (Lackey et al. 2006, Baldo et al. 2000). In accordance with the predictions of quantum chromodynamics, deconfined quark matter may also be produced there. When

the highly compressed matter could undergo the deconfinement phase transition into u, d, s quark matter, or according to absolute stable strange quark matter hypothesis, the quark-hybrid star (A3-4, B2-3, C2-3) (Pan & Zheng 2007, Zheng et al. 2007, Alford et al. 2005, Nicotra et al. 2006, Fahri & Jaffe 1984) and strange star (D1) (Schertler et al. 1997) may exist. In Fig. 1, we compare various radius-mass relations with the observation data of SAX J1808.4-3658, of which the equations of state have been listed detailedly in Table 1. Obviously, only these softer equations of state could satisfy the inferred mass-radius region, and some of the neutron stars, hyperon stars, quark stars and strange stars match the observation well. But as predicted above, we can't tell the exact components in the core of this neutron star.

3.2. Rotation estimates

For a uniform rigid compact star with mass M and radius R , there exist some limits on the attainable rotation frequency. The most obvious one is the Keplerian limit (Lattimer & Prakash 2004)

$$\nu_K = 1.042 \times 10^3 \times \frac{(M/M_\odot)^{1/2}}{(R/10\text{km})^{3/2}} \text{Hz}, \quad (4)$$

which is also called the mass-shedding limit. When its spin frequency exceeds this limit, the matter near the equator would run away, and the star may be no longer stable. It is foreign to the material qualities of the matter inside. So if we get the frequency of observed pulsar and assume it to be the Keplerian limit, we can obtain a critical mass-radius relation to constrain the equations of state, which has been given as the cyan district in Fig. 1, but it also seems to have no help in distinguishing the composition of the super-nuclear matter even if the mass-radius method is considered together.

Actually, the emission of gravitational radiation following the excitation of non-radial oscillation modes may lead to the instability of rotating stars (Chandrasekhar 1970, Andersson 1998, Andersson & Kokkotas 2001), and the corresponding limiting rotation can be obtained via

$$\frac{1}{\tau_G} + \frac{1}{\tau_v} = 0. \quad (5)$$

Here $\tau_G < 0$ is the characteristic time scale for energy loss due to gravitational waves emission, and τ_v , the damping timescales due to shear, bulk viscosities and other rubbings, which relates to the viscosities of the matter inside neutron stars and their differences could result in diverse behaviors (Pan & Kang 2007).

In Fig. 2, we show the limit rotation frequencies for different classes of neutron stars under the relativistic mean field theory for demonstration, which is constructed by means of the method brought forward by Zheng et al. (2007). Clearly, these thick solid lines should be the genuine upper frequencies for each class. After matching our theoretical predictions with the observation data, we find that the traditional neutron star should be excluded, although its Keplerian limit could reach above the 401 Hz of SAX J1808.4-3658. While hyperon star, quark star and strange star are supposed to be the best candidates. Therefore, the star could contain either hyperons or quarks at super-nuclear region, but we can't tell them from each other. We should emphasize that, the conclusion is still true if we apply it to various classes of neutron stars under other approaches.

4. Conclusions

The composition of matter in the core of neutron stars has attracted much attention owing to its important significance. Up

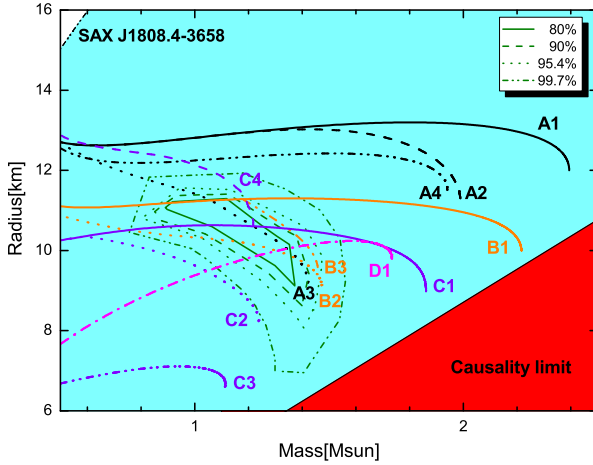


Fig. 1. Radius-mass relations for various equations of state of compact stars listed in Table 1. The red and cyan districts refer to the causality limit and simply traditional Keplerian rotation limit at 2.49 ms discovered by Wijnands and van der Klis (1998) respectively. These green contours correspond to 80%, 90%, 95.4% and 99.7% confidence levels of the X-ray pulsar in SAX J1808.4-3658 analyzed by Leahy et al. (2007). Note that we here use the non-rotating approximation in the calculation, as the radii and masses of these stars are about 10% and 2-3% larger due to the rotation correction at 2.49 ms, which couldn't affect our results significantly.

to now, SAX J1808.4-3658 is one of seven known accreting ms X-ray pulsar. Its persistent 2.49 ms X-ray pulsations was discovered by Wijnands and van der Klis and interpreted as due to the ms rotation of the center neutron star. And Leahy et al. have analyzed its corresponding mass-radius relation. In our estimation, we try to probe the inner components of it in our own way by comparing the mass-radius relations and genuine rotation frequencies under different theoretical models with the observational data. We finally come to a conclusion that the pulsar in SAX J1808.4-3658 is a star containing exotic matter, which just bases on these two observational properties, but we can't distinguish it with hyperon matter from quark matter at the present time, which must depend on more observational information about it, such as the thermal emission data.

Acknowledgements.

This work is supported by the National Natural Science Foundation of China under Grant Nos. 10773004 and 10603002.

References

- Akmal A., Pandharipande V. R. and Ravenhall D. G. 1998, Phys. Rev. C., 58, 1804
 Alford M. et al. 2005, ApJ, 629, 969
 Alford M. & Reddy S. 2003, Phys. Rev. D., 67, 074024
 Andersson N. 1998, ApJ, 502, 708
 Andersson N. & Kokkotas K. D. 2001, Int. J. Mod. Phys. D., 10, 381
 Baldo M., Burgio G. F. and Schulze H. -J. 2000, Phys. Rev. C., 61, 055801
 Chandrasekhar S. 1970, Phys. Rev. Lett., 24, 611
 Fahri E. & Jaffe R. L. 1984, Phys. Rev. D., 30, 2379
 Glendenning N. K. 1985, ApJ, 293, 470
 Glendenning N. K. 1997, Compact stars, Springer-Verlag

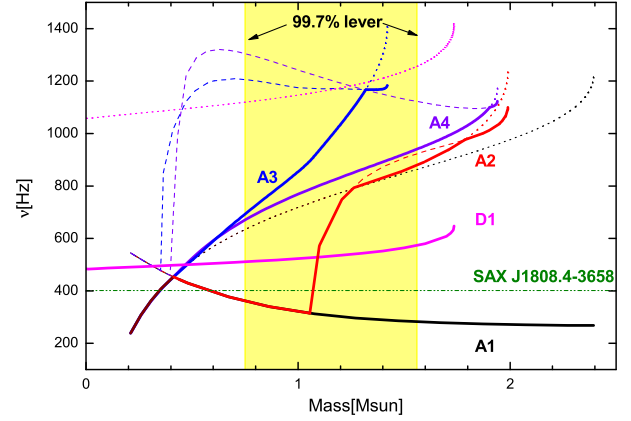


Fig. 2. Limit rotation frequencies for various equations of state of compact stars. These dashed lines represent the r-mode instability limits, and dotted lines the Keplerian limits. The corresponding thick solid lines are the genuine upper frequencies. The light yellow district refers to the mass prediction of the X-ray pulsar in SAX J1808.4-3658 at 99.7% confidence level analyzed by Leahy et al. (2007), and the green dash-dot-dot horizontal line the corresponding 2.49 ms rotation frequency discovered by Wijnands and van der Klis (1998).

- Glendenning N. K. & Moszkowski S. A. 1991, Phys. Rev. Lett., 67, 2414
 Glendenning N. K., Weber F. and Moszkowski S. A. 1992, Phys. Rev. C., 45, 844
 Gold T. & Pacini F. 1968, ApJ, 152, L115
 Hartle J. B. 1967, ApJ, 150, 1005
 Hartle J. B. & Thorne K. S. 1968, ApJ, 153, 807
 Hewish A. et al. 1968, Nature, 217, 709
 Klähn J. et al. 2006, Phys. Rev. C., 74, 035802
 Lackey B. D., Nayyar M. and Owen B. J. 2006, Phys. Rev. D., 73, 024021
 Lattimer J. M. & Prakash M. 2004, Science, 304, 536
 Lattimer J. M. & Prakash M. 2007, Phys. Rep., 442, 109
 Lavagetto G. et al. 2006, arXiv:astro-ph/0612061
 Leahy D. A., Morsink S. M. and Cadeau C. 2008, ApJ, 672, 1119
 Nicotra O. E. et al. 2006, Astron. Astrophys., 451, 213
 Oppenheimer J. R. & Volkoff G. M. 1939, Phys. Rev., 55, 374
 Pan N. N. & Kang M. 2007, arXiv:astro-ph/0709.4547
 Pan N. N. & Zheng X. P. 2007, Chin. J. Astron. Astrophys., 7, 675
 Pandharipande V. R. 1971, Nucl. Phys. A., 178, 123
 Sahu P. K., Basu R. and Datta B. 1993, ApJ, 416, 267
 Schertler K., Greiner C. and Thoma M. H. 1997, Nucl. Phys. A., 616, 659
 Thorsson V., Prakash M. and Lattimer J. M. 1994, Nucl. Phys. A., 572, 693
 Tolman R. C. 1939, Phys. Rev., 55, 364
 Wijnands R. & van der Klis M. 1998, Nature, 394, 344
 Zheng X. P., Pan N. N. and Zhang L. 2007, arXiv:astro-ph/0712.4310